Higgs Bosons — H^0 and $H^{\pm}$, Searches for

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STANDARD MODEL H^0 (Higgs Boson) MASS LIMITS

These limits apply to the Higgs boson of the three-generation Standard Model with the minimal Higgs sector. For a review and a bibliography, see the above Note on 'Searches for Higgs Bosons' by P. Igo-Kemenes.

Limits from Coupling to $Z/W^{\pm}$

Limits on the Standard Model Higgs obtained from the study of Z^0 decays rule out conclusively its existence in the whole mass region $m_{H^0} \lesssim 60$ GeV. These limits, as well as stronger limits obtained from e^+e^- collisions at LEP at energies up to 202 GeV, and weaker limits obtained from other sources, have been superseded by the most recent data of LEP. They have been removed from this compilation, and are documented in previous editions of this Review of Particle Physics.

In this Section, unless otherwise stated, limits from the four LEP experiments (ALEPH, DELPHI, L3, and OPAL) are obtained from the study of the $e^+e^- \rightarrow H^0 Z$ process, at center-of-mass energies reported in the comment lines.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>114.1	95	[1] ABDALLAH	04	DLPH	$E_{cm} \leq 209$ GeV
>112.7	95	[1] ABBIENDI	03B	OPAL	$E_{cm} \leq 209$ GeV
>114.4	95	[1,2] HEISTER	03D	LEP	$E_{cm} \leq 209$ GeV
>111.5	95	[1,3] HEISTER	02	ALEP	$E_{cm} \leq 209$ GeV
>112.0	95	[1] ACHARD	01C	L3	$E_{cm} \leq 209$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[4] ABAZOV	06	D0	$p\overline{p} \rightarrow H^0 X$, $H^0 \rightarrow WW^*$
		[5] ABAZOV	06O	D0	$p\overline{p} \rightarrow H^0 WX$, $H^0 \rightarrow WW^*$
		[6] ABAZOV	06Q	D0	$p\overline{p} \rightarrow H^0 ZX$
		[7] ABAZOV	06Q	D0	$p\overline{p} \rightarrow H^0 WX$
		[8] ABULENCIA	06H	CDF	$p\overline{p} \rightarrow H^0 WX$
		[9] ABULENCIA,A	06A	CDF	$p\overline{p} \rightarrow H^0 X$, $H^0 \rightarrow WW^*$
		[10] ABAZOV	05F	D0	$p\overline{p} \rightarrow H^0 WX$
		[11] ACOSTA	05K	CDF	$p\overline{p} \rightarrow H^0 ZX$
		[12] ABAZOV	01E	D0	$p\overline{p} \rightarrow H^0 WX$, $H^0 ZX$
		[13] ABE	98T	CDF	$p\overline{p} \rightarrow H^0 WX$, $H^0 ZX$

[1] Search for $e^+e^- \rightarrow H^0 Z$ in the final states $H^0 \rightarrow b\overline{b}$ with $Z \rightarrow \ell\overline{\ell}$, $\nu\overline{\nu}$, $q\overline{q}$, $\tau^+\tau^-$ and $H^0 \rightarrow \tau^+\tau^-$ with $Z \rightarrow q\overline{q}$.

[2] Combination of the results of all LEP experiments.

[3] A 3σ excess of candidate events compatible with m_{H^0} near 114 GeV is observed in the combined channels $q\overline{q}q\overline{q}$, $q\overline{q}\ell\overline{\ell}$, $q\overline{q}\tau^+\tau^-$.

[4] ABAZOV 06 search for Higgs boson production in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with the decay chain $H^0 \rightarrow WW^* \rightarrow \ell^+\nu\ell'\overline{\nu}$. A limit $\sigma(H^0)\cdot B(H0 \rightarrow WW^*) <$ (3.9–9.5) pb (95 %CL) is given for $m_{H^0} = 120$–200 GeV, which far exceeds the expected Standard Model cross section.

[5] ABAZOV 06O search for associated $H^0 W$ production in $p\overline{p}$ collisions at E_{cm} = 1.96 TeV with the decay $H^0 \rightarrow W W^*$, in the final states $\ell^{\pm}\ell^{\mp}\nu\nu X$ where $\ell = e, \mu$. A limit $\sigma(H^0 W)\cdot$ B($H^0 \rightarrow W W^*$) < (3.2–2.8) pb (95 %CL) is given for m_{H^0} = 115–175 GeV, which far exceeds the expected Standard Model cross section.

[6] ABAZOV 06Q search for associated $H^0 Z$ production in $p\overline{p}$ collisions at E_{cm} =1.96 TeV with $Z \rightarrow \nu\overline{\nu}$ and $H^0 \rightarrow b\overline{b}$. A limit $\sigma(H^0 Z)\cdot$ B($H^0 \rightarrow b\overline{b}$) < (3.4–2.5) pb (95% CL) for m_{H^0} = 105–135 GeV is derived, which is more than one order of magnitude larger than the expected Standard Model cross section.

[7] ABAZOV 06Q search for associated $H^0 W$ production in $p\overline{p}$ collisions at E_{cm} =1.96 TeV with $W \rightarrow \ell\nu$ (ℓ missing) and $H^0 \rightarrow b\overline{b}$. A limit $\sigma(H^0 W)\cdot$ B($H^0 \rightarrow b\overline{b}$) < (8.3–6.3) pb (95% CL) for m_{H^0} = 105–135 GeV is derived, which is more than one order of magnitude larger than the expected Standard Model cross section.

[8] ABULENCIA 06H search for associated $H^0 W$ production in $p\overline{p}$ collisions at E_{cm} = 1.96 TeV in the final state $W \rightarrow e\nu$, $\mu\nu$; $H^0 \rightarrow b\overline{b}$. A limit $\sigma(W H^0)\cdot$B($H^0 \rightarrow b\overline{b}$) < (10–3) pb (95% CL) is given for m_{H^0} = 110–150 GeV, which is more than 50 times larger than the expected Standard Model cross section.

[9] ABULENCIA,A 06A search for Higgs boson production in $p\overline{p}$ collisions at E_{cm} = 1.96 TeV with the decay chain $H^0 \rightarrow W W^* \rightarrow e^+ e^- \nu\overline{\nu}$, $e^{\pm}\mu^{\mp}\nu\overline{\nu}$, $\mu^+\mu^-\nu\overline{\nu}$. A limit $\sigma(H^0)\cdot$B($H^0 \rightarrow W W^*$) < (3.2–5.2) pb (95% CL) is given for m_{H^0} = 120–200 GeV, which far exceeds the expected Standard Model cross section.

[10] ABAZOV 05F search for associated $H^0 W$ production in $p\overline{p}$ collisions at E_{cm} = 1.96 TeV in the final state $W \rightarrow e\nu$, $H^0 \rightarrow b\overline{b}$. A limit $\sigma(W H^0)\cdot$B($H^0 \rightarrow b\overline{b}$) < [9.0, 9.1, 12.2] pb (95 %CL) is given for m_{H^0} = [115, 125, 135] GeV, which far exceeds the expected Standard Model cross section.

[11] ACOSTA 05K search for associated $H^0 Z$ production in $p\overline{p}$ collisions at E_{cm} = 1.8 TeV with $Z \rightarrow \ell\overline{\ell}$, $\nu\overline{\nu}$ and $H^0 \rightarrow b\overline{b}$. Combined with ABE 98T, a limit $\sigma(H^0 + W/Z)\cdot$B($H^0 \rightarrow b\overline{b}$) < (7.8–6.6) pb (95 %CL) for m_{H^0} = 90–130 GeV is derived, which is more than one order of magnitude larger than the expected Standard Model cross section.

[12] ABAZOV 01E search for associated $H^0 W$ and $H^0 Z$ production in $p\overline{p}$ collisions at E_{cm}= 1.8 TeV. The limits of $\sigma(H^0 W)\times$B($W \rightarrow e\nu$)$\times$B($H^0 \rightarrow q\overline{q}$) < 2.0 pb (95%CL) and $\sigma(H^0 Z)\times$B($Z \rightarrow e^+ e^-$)$\times$B($H^0 \rightarrow q\overline{q}$) < 0.8 pb (95%CL) are given for m_H=115 GeV.

[13] ABE 98T search for associated $H^0 W$ and $H^0 Z$ production in $p\overline{p}$ collisions at $\sqrt{s}$= 1.8 TeV with $W(Z) \rightarrow q\overline{q}^{(\prime)}$, $H^0 \rightarrow b\overline{b}$. The results are combined with the search in ABE 97W, resulting in the cross-section limit $\sigma(H^0 + W/Z)\cdot$B($H^0 \rightarrow b\overline{b}$)<(23–17) pb (95%CL) for m_H= 70–140 GeV. This limit is one to two orders of magnitude larger than the expected cross section in the Standard Model.

H^0 Indirect Mass Limits from Electroweak Analysis

For limits obtained before the direct measurement of the top quark mass, see the 1996 (Physical Review **D54** 1 (1996)) Edition of this Review. Other studies based on data available prior to 1996 can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this Review. For indirect limits obtained from other considerations of theoretical nature, see the Note on "Searches for Higgs Bosons."

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{129^{+74}_{-49}}$		[14] LEP-SLC	06	RVUE	

• • • We do not use the following data for averages, fits, limits, etc. • • •

		[15] CHANOWITZ	02	RVUE	
390^{+750}_{-280}		[16] ABBIENDI	01A	OPAL	
		[17] CHANOWITZ	99	RVUE	
<290	95	[18] D'AGOSTINI	99	RVUE	
<211	95	[19] FIELD	99	RVUE	
		[20] CHANOWITZ	98	RVUE	
$170^{+150}_{-\ 90}$		[21] HAGIWARA	98B	RVUE	
$141^{+140}_{-\ 77}$		[22] DEBOER	97B	RVUE	
$127^{+143}_{-\ 71}$		[23] DEGRASSI	97	RVUE	$\sin^2\theta_W$(eff,lept)
$158^{+148}_{-\ 84}$		[24] DITTMAIER	97	RVUE	
$149^{+148}_{-\ 82}$		[25] RENTON	97	RVUE	
$145^{+164}_{-\ 77}$		[26] ELLIS	96C	RVUE	
185^{+251}_{-134}		[27] GURTU	96	RVUE	

[14] LEP-SLC 06 make Standard Model fits to Z parameters from LEP/SLC and m_t, m_W, and Γ_W measurements available in 2005 with $\Delta\alpha^{(5)}_{\rm had}(m_Z) = 0.02758 \pm 0.00035$. The 95% CL limit is 285 GeV.

[15] CHANOWITZ 02 studies the impact for the prediction of the Higgs mass of two 3σ anomalies in the SM fits to electroweak data. It argues that the Higgs mass limit should not be trusted whether the anomalies originate from new physics or from systematic effects.

[16] ABBIENDI 01A make Standard Model fits to OPAL's measurements of Z-lineshape parameters and lepton forward-backward asymmetries, using m_t=174.3 ± 5.1 GeV and $1/\alpha(m_Z) = 128.90 \pm 0.09$. The fit also yields $\alpha_s(m_Z)$=0.127 ± 0.005. If the external value of $\alpha_s(m_Z)$=0.1184 ± 0.0031 is added to the fit, the result changes to $m_{H^0}=190^{+335}_{-165}$ GeV.

[17] CHANOWITZ 99 studies LEP/SLD data on 9 observables related $\sin^2\theta^{\ell}_{\rm eff}$, available in the Spring of 1998. A scale factor method is introduced to perform a global fit, in view of the conflicting data. m_H as large as 750 GeV is allowed at 95% CL.

[18] D'AGOSTINI 99 use m_t, m_W, and effective $\sin^2\theta_W$ from LEP/SLD available in the Fall 1998 and combine with direct Higgs search constraints from LEP2 at $E_{\rm cm}$=183 GeV. $\alpha(m_Z)$ given by DAVIER 98.

[19] FIELD 99 studies the data on b asymmetries from $Z^0 \rightarrow b\overline{b}$ decays at LEP and SLD (from LEP 99). The limit uses $1/\alpha(M_Z)$= 128.90 ± 0.09, the variation in the fitted top quark mass, $m_t=171.2^{+3.7}_{-3.8}$ GeV, and excludes b-asymmetry data. It is argued that exclusion of these data, which deviate from the Standard Model expectation, from the electroweak fits reduces significantly the upper limit on m_H. Including the b-asymmetry data gives instead the 95%CL limit $m_H < 284$ GeV. See also FIELD 00.

[20] CHANOWITZ 98 fits LEP and SLD Z-decay-asymmetry data (as reported in ABBANEO 97), and explores the sensitivity of the fit to the weight ascribed to measurements that are individually in significant contradiction with the direct-search limits. Various prescriptions are discussed, and significant variations of the 95%CL Higgs-mass upper limits are found. The Higgs-mass central value varies from 100 to 250 GeV and the 95%CL upper limit from 340 GeV to the TeV scale.

[21] HAGIWARA 98B fit to LEP, SLD, W mass, and neutrino scattering data as reported in ALCARAZ 96, with $m_t = 175 \pm 6$ GeV, $1/\alpha(m_Z) = 128.90 \pm 0.09$ and $\alpha_s(m_Z) = 0.118 \pm 0.003$. Strong dependence on m_t is found.

[22] DEBOER 97B fit to LEP and SLD data (as reported in ALCARAZ 96), as well as m_W and m_t from CDF/DØ and CLEO $b \to s\gamma$ data (ALAM 95). $1/\alpha(m_Z) = 128.90 \pm 0.09$ and $\alpha_s(m_Z) = 0.120 \pm 0.003$ are used. Exclusion of SLC data yields $m_H = 241^{+218}_{-123}$ GeV. $\sin^2\theta_{\mathrm{eff}}$ from SLC (0.23061 ± 0.00047) would give $m_H = 16^{+16}_{-9}$ GeV.

[23] DEGRASSI 97 is a two-loop calculation of M_W and $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ as a function of m_H, using $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ 0.23165(24) as reported in ALCARAZ 96, $m_t = 175 \pm 6$ GeV, and $1/\alpha(m_Z) = 128.90 \pm 0.09$.

[24] DITTMAIER 97 fit to m_W and LEP/SLC data as reported in ALCARAZ 96, with $m_t = 175 \pm 6$ GeV, $1/\alpha(m_Z^2) = 128.89 \pm 0.09$. Exclusion of the SLD data gives $m_H = 261^{+224}_{-128}$ GeV. Taking only the data on m_t, m_W, $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$, and Γ^{lept}_Z, the authors get $m_H = 190^{+174}_{-102}$ GeV and $m_H = 296^{+243}_{-143}$ GeV, with and without SLD data, respectively. The 95% CL upper limit is given by 550 GeV (800 GeV removing the SLD data).

[25] RENTON 97 fit to LEP and SLD data (as reported in ALCARAZ 96), as well as m_W and m_t from $p\overline{p}$, and low-energy νN data available in early 1997. $1/\alpha(m_Z) = 128.90 \pm 0.09$ is used.

[26] ELLIS 96C fit to LEP, SLD, m_W, neutral-current data available in the summer of 1996, plus $m_t = 175 \pm 6$ GeV from CDF/DØ . The fit yields $m_t = 172 \pm 6$ GeV.

[27] GURTU 96 studies the effect of the mutually incompatible SLD and LEP asymmetry data on the determination of m_H. Use is made of data available in the Summer of 1996. The quoted value is obtained by increasing the errors *à la* PDG. A fit ignoring the SLD data yields 267^{+242}_{-135} GeV.

MASS LIMITS FOR NEUTRAL HIGGS BOSONS IN SUPERSYMMETRIC MODELS

The minimal supersymmetric model has two complex doublets of Higgs bosons. The resulting physical states are two scalars [H_1^0 and H_2^0, where we define $m_{H_1^0} < m_{H_2^0}$], a pseudoscalar (A^0), and a charged Higgs pair ($H^\pm$). H_1^0 and H_2^0 are also called h and H in the literature. There are two free parameters in the theory which can be chosen to be m_{A^0} and $\tan\beta = v_2/v_1$, the ratio of vacuum expectation values of the two Higgs doublets. Tree-level Higgs masses are constrained by the model to be $m_{H_1^0} \leq m_Z$, $m_{H_2^0} \geq m_Z$, $m_{A^0} \geq m_{H_1^0}$, and $m_{H^\pm} \geq m_W$. However, as described in the Review on Supersymmetry in this Volume these relations are violated by radiative corrections.

Unless otherwise noted, the experiments in e^+e^- collisions search for the processes $e^+e^- \to H_1^0 Z^0$ in the channels used for the Standard Model Higgs searches and $e^+e^- \to H_1^0 A^0$ in the final states $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$. Limits on the A^0 mass arise from these direct searches, as well as from the relations valid in the minimal supersymmetric model between m_{A^0} and $m_{H_1^0}$. As discussed in the minireview on Supersymmetry, in this volume, these relations depend on the masses of the t quark and $\widetilde{t}$ squark.

The limits are weaker for larger t and $\widetilde{t}$ masses, while they increase with the inclusion of two-loop radiative corrections. To include the radiative corrections to the Higgs masses, unless otherwise stated, the listed papers use the two-loop results with $m_t = 175$ GeV, the universal scalar mass of 1 TeV, SU(2) gaugino mass of 200 GeV, and the Higgsino mass parameter $\mu = -200$ GeV, and examine the two scenarios of no scalar top mixing and 'maximal' stop mixing (which maximizes the effect of the radiative correction).

The mass region $m_{H_1^0} \lesssim 45$ GeV has been by now entirely ruled out by measurements at the Z pole. The relative limits, as well as other by now obsolete limits from different techniques, have been removed from this compilation, and can be found in earlier editions of this Review. Unless otherwise stated, the following results assume no invisible H_1^0 or A^0 decays.

H_1^0 (Higgs Boson) MASS LIMITS in Supersymmetric Models

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 92.8	95	[28] SCHAEL	06B	LEP	
> 84.5	95	[29,30] ABBIENDI	04M	OPAL	$E_{cm} \leq 209$ GeV
> 89.7	95	[29,31] ABDALLAH	04	DLPH	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.4$
> 86.0	95	[29,32] ACHARD	02H	L3	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.4$
>100	95	[33] AFFOLDER	01D	CDF	$p\overline{p} \to b\overline{b}H_1^0$, $\tan\beta \gtrsim 55$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[34] ABBIENDI	03G	OPAL	$H_1^0 \to A^0 A^0$
> 89.8	95	[29,35] HEISTER	02	ALEP	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.5$

[28] SCHAEL 06B make a combined analysis of the LEP data. The quoted limit is for the m_h-max scenario with $m_t = 174.3$ GeV. In the *CP*-violating CPX scenario no lower bound on $m_{H_1^0}$ can be set at 95% CL. See paper for excluded regions in various scenarios. See Figs. 2–6 and Tabs. 14–21 for limits on $\sigma(Z H^0)\cdot B(H^0 \to b\overline{b}, \tau^+\tau^-)$ and $\sigma(H_1^0 H_2^0)\cdot B(H_1^0, H_2^0 \to b\overline{b}, \tau^+\tau^-)$.

[29] Search for $e^+e^- \to H_1^0 A^0$ in the final states $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$, and $e^+e^- \to H_1^0 Z$. Universal scalar mass of 1 TeV, SU(2) gaugino mass of 200 GeV, and $\mu = -200$ GeV are assumed, and two-loop radiative corrections incorporated. The limits hold for m_t=175 GeV, and for the so-called "m_h-max scenario" (CARENA 99B).

[30] ABBIENDI 04M exclude $0.7 < \tan\beta < 1.9$, assuming $m_t = 174.3$ GeV. Limits for other MSSM benchmark scenarios, as well as for *CP* violating cases, are also given.

[31] This limit applies also in the no-mixing scenario. Furthermore, ABDALLAH 04 excludes the range $0.54 < \tan\beta < 2.36$. The limit improves in the region $\tan\beta < 6$ (see Fig. 28). Limits for $\mu = 1$ TeV are given in Fig. 30.

[32] ACHARD 02H also search for the final state $H_1^0 Z \to 2A^0 q\overline{q}$, $A^0 \to q\overline{q}$. In addition, the MSSM parameter set in the "large-μ" and "no-mixing" scenarios are examined.

[33] AFFOLDER 01D search for final states with 3 or more b-tagged jets. See Figs. 2 and 3 for Higgs mass limits as a function of $\tan\beta$, and for different stop mixing scenarios. Stronger limits are obtained at larger $\tan\beta$ values.

[34] ABBIENDI 03G search for $e^+e^- \to H_1^0 Z$ followed by $H_1^0 \to A^0 A^0$, $A^0 \to c\overline{c}$, gg, or $\tau^+\tau^-$. In the no-mixing scenario, the region $m_{H_1^0}$ = 45-85 GeV and m_{A^0} = 2-9.5 GeV is excluded at 95% CL.

[35] HEISTER 02 excludes the range $0.7 < \tan\beta < 2.3$. A wider range is excluded with different stop mixing assumptions. Updates BARATE 01C.

A^0 (Pseudoscalar Higgs Boson) MASS LIMITS in Supersymmetric Models

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 93.4	95	[36] SCHAEL	06B	LEP	
> 85.0	95	[37,38] ABBIENDI	04M	OPAL	$E_{cm} \leq 209$ GeV
> 90.4	95	[37,39] ABDALLAH	04	DLPH	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.4$
> 86.5	95	[37,40] ACHARD	02H	L3	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.4$
> 90.1	95	[37,41] HEISTER	02	ALEP	$E_{cm} \leq 209$ GeV, $\tan\beta > 0.5$
>100	95	[42] AFFOLDER	01D	CDF	$p\overline{p} \rightarrow b\overline{b}A^0$, $\tan\beta \gtrsim 55$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[43] ABAZOV	06J	D0	$p\overline{p} \rightarrow H^0 X$, $H^0 \rightarrow \tau^+\tau^-$
		[44] ABULENCIA	06	CDF	$p\overline{p} \rightarrow H^0_{1,2}/A^0 + X$
		[45] ABAZOV	05T	D0	$p\overline{p} \rightarrow b\overline{b}H^0_{1,2}/A^0 + X$
		[46] ACOSTA	05Q	CDF	$p\overline{p} \rightarrow H^0_{1,2}/A^0 + X$
		[47] ABBIENDI	03G	OPAL	$H^0_1 \rightarrow A^0 A^0$
		[48] AKEROYD	02	RVUE	

[36] SCHAEL 06B make a combined analysis of the LEP data. The quoted limit is for the m_h-max scenario with $m_t = 174.3$ GeV. In the *CP*-violating CPX scenario no lower bound on $m_{H^0_1}$ can be set at 95% CL. See paper for excluded regions in various scenarios. See Figs. 2–6 and Tabs. 14–21 for limits on $\sigma(Z H^0)\cdot \mathrm{B}(H^0 \rightarrow b\overline{b}, \tau^+\tau^-)$ and $\sigma(H^0_1 H^0_2)\cdot \mathrm{B}(H^0_1,H^0_2 \rightarrow b\overline{b},\tau^+\tau^-)$.

[37] Search for $e^+e^- \rightarrow H^0_1 A^0$ in the final states $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$, and $e^+e^- \rightarrow H^0_1 Z$. Universal scalar mass of 1 TeV, SU(2) gaugino mass of 200 GeV, and $\mu = -200$ GeV are assumed, and two-loop radiative corrections incorporated. The limits hold for m_t=175 GeV, and for the so-called "m_h-max scenario" (CARENA 99B).

[38] ABBIENDI 04M exclude $0.7 < \tan\beta < 1.9$, assuming $m_t = 174.3$ GeV. Limits for other MSSM benchmark scenarios, as well as for *CP* violating cases, are also given.

[39] This limit applies also in the no-mixing scenario. Furthermore, ABDALLAH 04 excludes the range $0.54 < \tan\beta < 2.36$. The limit improves in the region $\tan\beta < 6$ (see Fig. 28). Limits for $\mu = 1$ TeV are given in Fig. 30.

[40] ACHARD 02H also search for the final state $H^0_1 Z \rightarrow 2A^0 q\overline{q}$, $A^0 \rightarrow q\overline{q}$. In addition, the MSSM parameter set in the "large-μ" and "no-mixing" scenarios are examined.

[41] HEISTER 02 excludes the range $0.7 < \tan\beta < 2.3$. A wider range is excluded with different stop mixing assumptions. Updates BARATE 01C.

[42] AFFOLDER 01D search for final states with 3 or more *b*-tagged jets. See Figs. 2 and 3 for Higgs mass limits as a function of $\tan\beta$, and for different stop mixing scenarios. Stronger limits are obtained at larger $\tan\beta$ values.

[43] ABAZOV 06J search for Higgs boson production in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with the decay $H^0_{1,2}$, $A^0 \rightarrow \tau^+\tau^-$. See their Fig. 3 for the region in the MSSM parameter space excluded by this analysis and the results or ABAZOV 05T.

[44] ABULENCIA 06 search for $H^0_{1,2}/A^0$ production in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with $H^0_{1,2}/A^0 \rightarrow \tau^+\tau^-$. A region with $\tan\beta > 40$ (100) is excluded for $m_{A^0} = 90$ (170) GeV.

[45] ABAZOV 05T search for $H^0_{1,2}/A^0$ production in association with bottom quarks in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV, with the $b\overline{b}$ decay mode. See their Fig. 5 for the excluded parameter regions in the m_h-max and no-mixing scenarios for $\mu = -200$ GeV.

[46] ACOSTA 05Q search for $H^0_{1,2}/A^0$ production in $p\overline{p}$ collisions at E_{cm} = 1.8 TeV with $H^0_{1,2}/A^0 \rightarrow \tau^+\tau^-$. At m_{A^0} = 100 GeV, the obtained cross section upper limit is above theoretical expectation.

[47] ABBIENDI 03G search for $e^+e^- \rightarrow H^0_1 Z$ followed by $H^0_1 \rightarrow A^0 A^0$, $A^0 \rightarrow c\overline{c}$, gg, or $\tau^+\tau^-$. In the no-mixing scenario, the region $m_{H^0_1}$ = 45-85 GeV and m_{A^0} = 2-9.5 GeV is excluded at 95% CL.

[48] AKEROYD 02 examine the possibility of a light A^0 with $\tan\beta$ <1. Electroweak measurements are found to be inconsistent with such a scenario.

H^0 (Higgs Boson) MASS LIMITS in Extended Higgs Models

This Section covers models which do not fit into either the Standard Model or its simplest minimal Supersymmetric extension (MSSM), leading to anomalous production rates, or nonstandard final states and branching ratios. In particular, this Section covers limits which may apply to generic two-Higgs-doublet models (2HDM), or to special regions of the MSSM parameter space where decays to invisible particles or to photon pairs are dominant (see the Note on 'Searches for Higgs Bosons' at the beginning of this Chapter). See the footnotes or the comment lines for details on the nature of the models to which the limits apply.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 1–55	95	[49] ABBIENDI	05A	OPAL	H^0_1, Type II model
none 3–63	95	[49] ABBIENDI	05A	OPAL	A^0, Type II model
>110.6	95	[50] ABDALLAH	05D	DLPH	$H^0 \rightarrow$ 2 jets
>112.3	95	[51] ACHARD	05	L3	invisible H^0
>104	95	[52] ABBIENDI	04K	OPAL	$H^0 \rightarrow$ 2 jets
		[53] ABDALLAH	04	DLPH	$H^0 VV$ couplings
>112.1	95	[51] ABDALLAH	04B	DLPH	Invisible H^0
>104.1	95	[54,55] ABDALLAH	04L	DLPH	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$
		[56] ABDALLAH	04O	DLPH	$Z \rightarrow f\overline{f}H$
		[57] ABDALLAH	04O	DLPH	$e^+e^- \rightarrow H^0 Z$, $H^0 A^0$
>110.3	95	[58] ACHARD	04B	L3	$H^0 \rightarrow$ 2 jets
		[59] ACHARD	04F	L3	Anomalous coupling
		[60] ABBIENDI	03F	OPAL	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow$ any
		[61] ABBIENDI	03G	OPAL	$H^0_1 \rightarrow A^0 A^0$
>107	95	[62] ACHARD	03C	L3	$H^0 \rightarrow WW^*, ZZ^*, \gamma\gamma$
		[63] ABBIENDI	02D	OPAL	$e^+e^- \rightarrow b\overline{b}H$
>105.5	95	[54,64] ABBIENDI	02F	OPAL	$H^0_1 \rightarrow \gamma\gamma$
>105.4	95	[65] ACHARD	02C	L3	$H^0_1 \rightarrow \gamma\gamma$
>114.1	95	[51] HEISTER	02	ALEP	Invisible H^0, $E_{cm} \leq$ 209 GeV
>105.4	95	[54,66] HEISTER	02L	ALEP	$H^0_1 \rightarrow \gamma\gamma$
>109.1	95	[67] HEISTER	02M	ALEP	$H^0 \rightarrow$ 2 jets or $\tau^+\tau^-$
none 1–44	95	[68] ABBIENDI	01E	OPAL	H^0_1, Type-II model
none 12–56	95	[68] ABBIENDI	01E	OPAL	A^0, Type-II model
> 98	95	[69] AFFOLDER	01H	CDF	$p\overline{p} \rightarrow H^0 W/Z$, $H^0 \rightarrow \gamma\gamma$
>106.4	95	[51] BARATE	01C	ALEP	Invisible H^0, $E_{cm} \leq$ 202 GeV
> 89.2	95	[70] ACCIARRI	00M	L3	Invisible H^0

		[71] ACCIARRI	00R	L3	$e^+e^- \to H^0\gamma$ and/or $H^0 \to \gamma\gamma$
		[72] ACCIARRI	00R	L3	$e^+e^- \to e^+e^- H^0$
$>$ 94.9	95	[73] ACCIARRI	00S	L3	$e^+e^- \to H^0 Z$, $H^0 \to \gamma\gamma$
$>$100.7	95	[74] BARATE	00L	ALEP	$e^+e^- \to H^0 Z$, $H^0 \to \gamma\gamma$
$>$ 68.0	95	[75] ABBIENDI	99E	OPAL	$\tan\beta > 1$
$>$ 96.2	95	[76] ABBIENDI	99O	OPAL	$e^+e^- \to H^0 Z$, $H^0 \to \gamma\gamma$
$>$ 78.5	95	[77] ABBOTT	99B	D0	$p\overline{p} \to H^0 W/Z$, $H^0 \to \gamma\gamma$
		[78] ABREU	99P	DLPH	$e^+e^- \to H^0\gamma$ and/or $H^0 \to \gamma\gamma$
		[79] GONZALEZ-G..98B		RVUE	Anomalous coupling
		[80] KRAWCZYK	97	RVUE	$(g-2)_\mu$
		[81] ALEXANDER	96H	OPAL	$Z \to H^0\gamma$
		[82] ABREU	95H	DLPH	$Z \to H^0 Z^*$, $H^0 A^0$
		[83] PICH	92	RVUE	Very light Higgs

[49] ABBIENDI 05A search for $e^+e^- \to H_1^0 A^0$ in general Type-II two-doublet models, with decays H_1^0, $A^0 \to q\overline{q}$, gg, $\tau^+\tau^-$, and $H_1^0 \to A^0 A^0$.

[50] ABDALLAH 05D search for $e^+e^- \to H^0 Z$ and $H^0 A^0$ with H^0, A^0 decaying to two jets of any flavor including gg. The limit is for SM $H^0 Z$ production cross section with $\mathrm{B}(H^0 \to jj) = 1$.

[51] Search for $e^+e^- \to H^0 Z$ with H^0 decaying invisibly. The limit assumes SM production cross section and $\mathrm{B}(H^0 \to \text{invisible}) = 1$.

[52] ABBIENDI 04K search for $e^+e^- \to H^0 Z$ with H^0 decaying to two jets of any flavor including gg. The limit is for SM production cross section with $\mathrm{B}(H^0 \to jj) = 1$.

[53] ABDALLAH 04 consider the full combined LEP and LEP2 datasets to set limits on the Higgs coupling to W or Z bosons, assuming SM decays of the Higgs. Results in Fig. 26.

[54] Search for associated production of a $\gamma\gamma$ resonance with a Z boson, followed by $Z \to q\overline{q}$, $\ell^+\ell^-$, or $\nu\overline{\nu}$, at $E_{\mathrm{cm}} \le 209$ GeV. The limit is for a H^0 with SM production cross section and $\mathrm{B}(H^0 \to f\overline{f})=0$ for all fermions f.

[55] Updates ABREU 01F.

[56] ABDALLAH 04O search for $Z \to b\overline{b}H^0$, $b\overline{b}A^0$, $\tau^+\tau^- H^0$ and $\tau^+\tau^- A^0$ in the final states $4b$, $b\overline{b}\tau^+\tau^-$, and 4τ. See paper for limits on Yukawa couplings.

[57] ABDALLAH 04O search for $e^+e^- \to H^0 Z$ and $H^0 A^0$, with H^0, A^0 decaying to $b\overline{b}$, $\tau^+\tau^-$, or $H^0 \to A^0 A^0$ at $E_{\mathrm{cm}} = 189$–208 GeV. See paper for limits on couplings.

[58] ACHARD 04B search for $e^+e^- \to H^0 Z$ with H^0 decaying to $b\overline{b}$, $c\overline{c}$, or gg. The limit is for SM production cross section with $\mathrm{B}(H^0 \to jj) = 1$.

[59] ACHARD 04F search for H^0 with anomalous coupling to gauge boson pairs in the processes $e^+e^- \to H^0\gamma$, $e^+e^- H^0$, $H^0 Z$ with decays $H^0 \to f\overline{f}$, $\gamma\gamma$, $Z\gamma$, and $W^* W$ at $E_{\mathrm{cm}} = 189$–209 GeV. See paper for limits.

[60] ABBIENDI 03F search for $H^0 \to$ anything in $e^+e^- \to H^0 Z$, using the recoil mass spectrum of $Z \to e^+e^-$ or $\mu^+\mu^-$. In addition, it searched for $Z \to \nu\overline{\nu}$ and $H^0 \to e^+e^-$ or photons. Scenarios with large width or continuum H^0 mass distribution are considered. See their Figs. 11–14 for the results.

[61] ABBIENDI 03G search for $e^+e^- \to H_1^0 Z$ followed by $H_1^0 \to A^0 A^0$, $A^0 \to c\overline{c}$, gg, or $\tau^+\tau^-$ in the region $m_{H_1^0} = 45$-86 GeV and $m_{A^0} = 2$-11 GeV. See their Fig. 7 for the limits.

[62] ACHARD 03C search for $e^+e^- \to Z H^0$ followed by $H^0 \to W W^*$ or $Z Z^*$ at $E_{\mathrm{cm}}=$ 200-209 GeV and combine with the ACHARD 02C result. The limit is for a H^0 with SM production cross section and $\mathrm{B}(H^0 \to f\overline{f}) = 0$ for all f. For $\mathrm{B}(H^0 \to W W^*) +$

B($H^0 \rightarrow ZZ^*$) = 1, $m_{H^0} > 108.1$ GeV is obtained. See fig. 6 for the limits under different BR assumptions.

[63] ABBIENDI 02D search for $Z \rightarrow b\overline{b}H_1^0$ and $b\overline{b}A^0$ with $H_1^0/A^0 \rightarrow \tau^+\tau^-$, in the range $4<m_H<12$ GeV. See their Fig. 8 for limits on the Yukawa coupling.

[64] For B($H^0 \rightarrow \gamma\gamma$)=1, $m_{H^0}>117$ GeV is obtained.

[65] ACHARD 02C search for associated production of a $\gamma\gamma$ resonance with a Z boson, followed by $Z \rightarrow q\overline{q}$, $\ell^+\ell^-$, or $\nu\overline{\nu}$, at $E_{cm} \leq 209$ GeV. The limit is for a H^0 with SM production cross section and B($H^0 \rightarrow f\overline{f}$)=0 for all fermions f. For B($H^0 \rightarrow \gamma\gamma$)=1, $m_{H^0}>114$ GeV is obtained.

[66] For B($H^0 \rightarrow \gamma\gamma$)=1, $m_{H^0} > 113.1$ GeV is obtained.

[67] HEISTER 02M search for $e^+e^- \rightarrow H^0 Z$, assuming that H^0 decays to $q\overline{q}$, gg, or $\tau^+\tau^-$ only. The limit assumes SM production cross section.

[68] ABBIENDI 01E search for neutral Higgs bosons in general Type-II two-doublet models, at $E_{cm} \leq 189$ GeV. In addition to usual final states, the decays H_1^0, $A^0 \rightarrow q\overline{q}$, gg are searched for. See their Figs. 15,16 for excluded regions.

[69] AFFOLDER 01H search for associated production of a $\gamma\gamma$ resonance and a W or Z (tagged by two jets, an isolated lepton, or missing E_T). The limit assumes Standard Model values for the production cross section and for the couplings of the H^0 to W and Z bosons. See their Fig. 11 for limits with B($H^0 \rightarrow \gamma\gamma$)$<1$.

[70] ACCIARRI 00M search for $e^+e^- \rightarrow ZH^0$ with H^0 decaying invisibly at E_{cm}=183–189 GeV. The limit assumes SM production cross section and B($H^0 \rightarrow$ invisible)=1. See their Fig. 6 for limits for smaller branching ratios.

[71] ACCIARRI 00R search for $e^+e^- \rightarrow H^0\gamma$ with $H^0 \rightarrow b\overline{b}$, $Z\gamma$, or $\gamma\gamma$. See their Fig. 3 for limits on $\sigma \cdot$B. Explicit limits within an effective interaction framework are also given, for which the Standard Model Higgs search results are used in addition.

[72] ACCIARRI 00R search for the two-photon type processes $e^+e^- \rightarrow e^+e^-H^0$ with $H^0 \rightarrow b\overline{b}$ or $\gamma\gamma$. See their Fig. 4 for limits on $\Gamma(H^0 \rightarrow \gamma\gamma)\cdot$B($H^0 \rightarrow \gamma\gamma$or $b\overline{b}$) for m_{H^0}=70–170 GeV.

[73] ACCIARRI 00S search for associated production of a $\gamma\gamma$ resonance with a $q\overline{q}$, $\nu\overline{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- collisions at E_{cm}= 189 GeV. The limit is for a H^0 with SM production cross section and B($H^0 \rightarrow f\overline{f}$)=0 for all fermions f. For B($H^0 \rightarrow \gamma\gamma$)=1, $m_{H^0} > 98$ GeV is obtained. See their Fig. 5 for limits on B($H \rightarrow \gamma\gamma$)$\cdot\sigma(e^+e^- \rightarrow Hf\overline{f})/\sigma(e^+e^- \rightarrow Hf\overline{f})$ (SM).

[74] BARATE 00L search for associated production of a $\gamma\gamma$ resonance with a $q\overline{q}$, $\nu\overline{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- collisions at E_{cm}= 88–202 GeV. The limit is for a H^0 with SM production cross section and B($H^0 \rightarrow f\overline{f}$)=0 for all fermions f. For B($H^0 \rightarrow \gamma\gamma$)=1, $m_{H^0} > 109$ GeV is obtained. See their Fig. 3 for limits on B($H \rightarrow \gamma\gamma$)$\cdot\sigma(e^+e^- \rightarrow Hf\overline{f})/\sigma(e^+e^- \rightarrow Hf\overline{f})$ (SM).

[75] ABBIENDI 99E search for $e^+e^- \rightarrow H^0A^0$ and H^0Z at E_{cm} = 183 GeV. The limit is with m_H=m_A in general two Higgs-doublet models. See their Fig. 18 for the exclusion limit in the m_H–m_A plane. Updates the results of ACKERSTAFF 98S.

[76] ABBIENDI 99O search for associated production of a $\gamma\gamma$ resonance with a $q\overline{q}$, $\nu\overline{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- collisions at 189 GeV. The limit is for a H^0 with SM production cross section and B($H^0 \rightarrow f\overline{f}$)=0, for all fermions f. See their Fig. 4 for limits on $\sigma(e^+e^- \rightarrow H^0Z^0)\times$B($H^0 \rightarrow \gamma\gamma$)$\times$B($X^0 \rightarrow f\overline{f}$) for various masses. Updates the results of ACKERSTAFF 98Y.

[77] ABBOTT 99B search for associated production of a $\gamma\gamma$ resonance and a dijet pair. The limit assumes Standard Model values for the production cross section and for the couplings of the H^0 to W and Z bosons. Limits in the range of $\sigma(H^0+Z/W)\cdot$B($H^0 \rightarrow \gamma\gamma$)= 0.80–0.34 pb are obtained in the mass range m_{H^0}= 65–150 GeV.

[78] ABREU 99P search for $e^+e^- \rightarrow H^0\gamma$ with $H^0 \rightarrow b\overline{b}$ or $\gamma\gamma$, and $e^+e^- \rightarrow H^0 q\overline{q}$ with $H^0 \rightarrow \gamma\gamma$. See their Fig. 4 for limits on $\sigma\times$B. Explicit limits within an effective interaction framework are also given.

[79] GONZALEZ-GARCIA 98B use DØ limit for $\gamma\gamma$ events with missing E_T in $p\overline{p}$ collisions (ABBOTT 98) to constrain possible ZH or WH production followed by unconventional $H \rightarrow \gamma\gamma$ decay which is induced by higher-dimensional operators. See their Figs. 1 and 2 for limits on the anomalous couplings.

[80] KRAWCZYK 97 analyse the muon anomalous magnetic moment in a two-doublet Higgs model (with type II Yukawa couplings) assuming no $H_1^0 ZZ$ coupling and obtain $m_{H_1^0} \gtrsim$ 5 GeV or $m_{A^0} \gtrsim$ 5 GeV for tan$\beta > 50$. Other Higgs bosons are assumed to be much heavier.

[81] ALEXANDER 96H give B($Z \rightarrow H^0\gamma$)$\times$B($H^0 \rightarrow q\overline{q}$) < 1–4×10^{-5} (95%CL) and B($Z \rightarrow H^0\gamma$)$\times$B($H^0 \rightarrow b\overline{b}$) < 0.7–2×10^{-5} (95%CL) in the range $20 < m_{H^0} < 80$ GeV.

[82] See Fig. 4 of ABREU 95H for the excluded region in the $m_{H^0} - m_{A^0}$ plane for general two-doublet models. For tan$\beta >1$, the region $m_{H^0}+m_{A^0} \lesssim 87$ GeV, $m_{H^0} <47$ GeV is excluded at 95% CL.

[83] PICH 92 analyse H^0 with $m_{H^0} <2m_\mu$ in general two-doublet models. Excluded regions in the space of mass-mixing angles from LEP, beam dump, and $\pi^\pm$, η rare decays are shown in Figs. 3,4. The considered mass region is not totally excluded.

$H^\pm$ (Charged Higgs) MASS LIMITS

Unless otherwise stated, the limits below assume B($H^+ \rightarrow \tau^+\nu$)+B($H^+ \rightarrow c\overline{s}$)=1, and hold for all values of B($H^+ \rightarrow \tau^+\nu_\tau$), and assume H^+ weak isospin of T_3=+1/2. In the following, tanβ is the ratio of the two vacuum expectation values in two-doublet models (2HDM).

The limits are also applicable to point-like technipions. For a discussion of techniparticles, see the Review of Dynamical Electroweak Symmetry Breaking in this Review.

For limits obtained in hadronic collisions before the observation of the top quark, and based on the top mass values inconsistent with the current measurements, see the 1996 (Physical Review **D54** 1 (1996)) Edition of this Review.

Searches in e^+e^- collisions at and above the Z pole have conclusively ruled out the existence of a charged Higgs in the region $m_{H^+} \lesssim 45$ GeV, and are now superseded by the most recent searches in higher energy e^+e^- collisions at LEP. Results by now obsolete are therefore not included in this compilation, and can be found in the previous Edition (The European Physical Journal **C15** 1 (2000)) of this Review.

In the following, and unless otherwise stated, results from the LEP experiments (ALEPH, DELPHI, L3, and OPAL) are assumed to derive from the study of the $e^+e^- \rightarrow H^+H^-$ process. Limits from $b \rightarrow s\gamma$ decays are usually stronger in generic 2HDM models than in Supersymmetric models.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>$ 74.4	95	ABDALLAH	04I	DLPH	$E_{cm} \leq 209$ GeV
$>$ 76.5	95	ACHARD	03E	L3	$E_{cm} \leq 209$ GeV
$>$ 79.3	95	HEISTER	02P	ALEP	$E_{cm} \leq 209$ GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

		[84] ABULENCIA	06E	CDF	$t \to bH^+$
> 92.0	95	ABBIENDI	04	OPAL	$B(\tau\nu) = 1$
> 76.7	95	[85] ABDALLAH	04I	DLPH	Type I
		[86] ABBIENDI	03	OPAL	$\tau \to \mu\overline{\nu}\nu,\ e\overline{\nu}\nu$
		[87] ABAZOV	02B	D0	$t \to bH^+,\ H \to \tau\nu$
		[88] BORZUMATI	02	RVUE	
		[89] ABBIENDI	01Q	OPAL	$B \to \tau\nu_\tau X$
		[90] BARATE	01E	ALEP	$B \to \tau\nu_\tau$
>315	99	[91] GAMBINO	01	RVUE	$b \to s\gamma$
		[92] AFFOLDER	00I	CDF	$t \to bH^+,\ H \to \tau\nu$
> 59.5	95	ABBIENDI	99E	OPAL	$E_{\rm cm} \le 183$ GeV
		[93] ABBOTT	99E	D0	$t \to bH^+$
		[94] ACKERSTAFF	99D	OPAL	$\tau \to e\nu\nu,\ \mu\nu\nu$
		[95] ACCIARRI	97F	L3	$B \to \tau\nu_\tau$
		[96] AMMAR	97B	CLEO	$\tau \to \mu\nu\nu$
		[97] COARASA	97	RVUE	$B \to \tau\nu_\tau X$
		[98] GUCHAIT	97	RVUE	$t \to bH^+,\ H \to \tau\nu$
		[99] MANGANO	97	RVUE	$B_{u(c)} \to \tau\nu_\tau$
		[100] STAHL	97	RVUE	$\tau \to \mu\nu\nu$
>244	95	[101] ALAM	95	CLE2	$b \to s\gamma$
		[102] BUSKULIC	95	ALEP	$b \to \tau\nu_\tau X$

[84] ABULENCIA 06E search for associated $H^0 W$ production in $p\overline{p}$ collisions at $E_{\rm cm} = 1.96$ TeV. A fit is made for $t\overline{t}$ production processes in dilepton, lepton + jets, and lepton + τ final states, with the decays $t \to W^+ b$ and $t \to H^+ b$ followed by $H^+ \to \tau^+\nu$, $c\overline{s}$, $t^*\overline{b}$, or $W^+ H^0$. Within the MSSM the search is sensitive to the region $\tan\beta < 1$ or > 30 in the mass range $m_{H^+} =$ 80–160 GeV. See Fig. 2 for the excluded region in a certain MSSM scenario.

[85] ABDALLAH 04I search for $e^+e^- \to H^+H^-$ with $H^\pm$ decaying to $\tau\nu$, cs, or $W^* A^0$ in Type-I two-Higgs-doublet models.

[86] ABBIENDI 03 give a limit $m_{H^+} > 1.28\tan\beta$ GeV (95%CL) in Type II two-doublet models.

[87] ABAZOV 02B search for a charged Higgs boson in top decays with $H^+ \to \tau^+\nu$ at $E_{\rm cm}$=1.8 TeV. For m_{H^+}=75 GeV, the region $\tan\beta > 32.0$ is excluded at 95%CL. The excluded mass region extends to over 140 GeV for $\tan\beta$ values above 100.

[88] BORZUMATI 02 point out that the decay modes such as $b\overline{b}W$, $A^0 W$, and supersymmetric ones can have substantial branching fractions in the mass range explored at LEP II and Tevatron.

[89] ABBIENDI 01Q give a limit $\tan\beta/m_{H^+} < 0.53$ GeV^{-1} (95%CL) in Type II two-doublet models.

[90] BARATE 01E give a limit $\tan\beta/m_{H^+} < 0.40$ GeV^{-1} (90% CL) in Type II two-doublet models. An independent measurement of $B \to \tau\nu_\tau X$ gives $\tan\beta/m_{H^+} < 0.49$ GeV^{-1} (90% CL).

[91] GAMBINO 01 use the world average data in the summer of 2001 $B(b \to s\gamma) = (3.23 \pm 0.42) \times 10^{-4}$. The limit applies for Type-II two-doublet models.

[92] AFFOLDER 00I search for a charged Higgs boson in top decays with $H^+ \to \tau^+\nu$ in $p\overline{p}$ collisions at $E_{\rm cm}$=1.8 TeV. The excluded mass region extends to over 120 GeV for $\tan\beta$ values above 100 and $B(\tau\nu)$=1. If $B(t \to bH^+) \gtrsim 0.6$, m_{H^+} up to 160 GeV is excluded. Updates ABE 97L.

[93] ABBOTT 99E search for a charged Higgs boson in top decays in $p\overline{p}$ collisions at $E_{\rm cm}$=1.8 TeV, by comparing the observed $t\overline{t}$ cross section (extracted from the data assuming the

dominant decay $t \rightarrow bW^+$) with theoretical expectation. The search is sensitive to regions of the domains $\tan\beta \lesssim 1$, $50 < m_{H^+}$(GeV) $\lesssim 120$ and $\tan\beta \gtrsim 40$, $50 < m_{H^+}$ (GeV) $\lesssim 160$. See Fig. 3 for the details of the excluded region.

[94] ACKERSTAFF 99D measure the Michel parameters ρ, ξ, η, and $\xi\delta$ in leptonic τ decays from $Z \rightarrow \tau\tau$. Assuming e-μ universality, the limit $m_{H^+} > 0.97 \tan\beta$ GeV (95%CL) is obtained for two-doublet models in which only one doublet couples to leptons.

[95] ACCIARRI 97F give a limit $m_{H^+} > 2.6 \tan\beta$ GeV (90% CL) from their limit on the exclusive $B \rightarrow \tau\nu_\tau$ branching ratio.

[96] AMMAR 97B measure the Michel parameter ρ from $\tau \rightarrow e\nu\nu$ decays and assumes e/μ universality to extract the Michel η parameter from $\tau \rightarrow \mu\nu\nu$ decays. The measurement is translated to a lower limit on m_{H^+} in a two-doublet model $m_{H^+} > 0.97 \tan\beta$ GeV (90% CL).

[97] COARASA 97 reanalyzed the constraint on the ($m_{H^\pm}$,$\tan\beta$) plane derived from the inclusive $B \rightarrow \tau\nu_\tau X$ branching ratio in GROSSMAN 95B and BUSKULIC 95. They show that the constraint is quite sensitive to supersymmetric one-loop effects.

[98] GUCHAIT 97 studies the constraints on m_{H^+} set by Tevatron data on $\ell\tau$ final states in $t\overline{t} \rightarrow (Wb)(Hb)$, $W \rightarrow \ell\nu$, $H \rightarrow \tau\nu_\tau$. See Fig. 2 for the excluded region.

[99] MANGANO 97 reconsiders the limit in ACCIARRI 97F including the effect of the potentially large $B_c \rightarrow \tau\nu_\tau$ background to $B_u \rightarrow \tau\nu_\tau$ decays. Stronger limits are obtained.

[100] STAHL 97 fit τ lifetime, leptonic branching ratios, and the Michel parameters and derive limit $m_{H^+} > 1.5 \tan\beta$ GeV (90% CL) for a two-doublet model. See also STAHL 94.

[101] ALAM 95 measure the inclusive $b \rightarrow s\gamma$ branching ratio at $\Upsilon(4S)$ and give $B(b \rightarrow s\gamma) < 4.2 \times 10^{-4}$ (95% CL), which translates to the limit $m_{H^+} > [244 + 63/(\tan\beta)^{1.3}]$ GeV in the Type II two-doublet model. Light supersymmetric particles can invalidate this bound.

[102] BUSKULIC 95 give a limit $m_{H^+} > 1.9 \tan\beta$ GeV (90% CL) for Type-II models from $b \rightarrow \tau\nu_\tau X$ branching ratio, as proposed in GROSSMAN 94.

MASS LIMITS for $H^{\pm\pm}$ (doubly-charged Higgs boson)

This section covers searches for a doubly-charged Higgs boson with couplings to lepton pairs. Its weak isospin T_3 is thus restricted to two possibilities depending on lepton chiralities: $T_3(H^{\pm\pm}) = \pm1$, with the coupling $g_{\ell\ell}$ to $\ell^-_L \ell'^-_L$ and $\ell^+_R \ell'^+_R$ ("left-handed") and $T_3(H^{\pm\pm}) = 0$, with the coupling to $\ell^-_R \ell'^-_R$ and $\ell^+_L \ell'^+_L$ ("right-handed"). These Higgs bosons appear in some left-right symmetric models based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)$. These two cases are listed separately in the following. Unless noted, one of the lepton flavor combinations is assumed to be dominant in the decay.

LIMITS for $H^{\pm\pm}$ with $T_3 = \pm1$

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>118.4	95	[103] ABAZOV	04E	D0	$\mu\mu$
>136	95	[104] ACOSTA	04G	CDF	$\mu\mu$
>98.1	95	[105] ABDALLAH	03	DLPH	$\tau\tau$
>99.0	95	[106] ABBIENDI	02C	OPAL	$\tau\tau$

• • • We do not use the following data for averages, fits, limits, etc. • • •

		[107] AKTAS	06A	H1	single $H^{\pm\pm}$
>133	95	[108] ACOSTA	05L	CDF	stable
		[109] ABBIENDI	03Q	OPAL	$E_{cm} \leq 209$ GeV, single $H^{\pm\pm}$
		[110] GORDEEV	97	SPEC	muonium conversion
		[111] ASAKA	95	THEO	
> 45.6	95	[112] ACTON	92M	OPAL	
> 30.4	95	[113] ACTON	92M	OPAL	
none 6.5–36.6	95	[114] SWARTZ	90	MRK2	

[103] ABAZOV 04E search for $H^{++}H^{--}$ pair production in $H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$. The limit is valid for $g_{\mu\mu} \gtrsim 10^{-7}$.

[104] ACOSTA 04G search for $H^{++}H^{--}$ pair production in $p\overline{p}$ collisions with muon and electron final states.The limit holds for $\mu\mu$. For ee and $e\mu$ modes, the limits are 133 and 115 GeV, respectively. The limits are valid for $g_{\ell\ell'} \gtrsim 10^{-5}$.

[105] ABDALLAH 03 search for $H^{++}H^{--}$ pair production either followed by $H^{++} \rightarrow \tau^{+}\tau^{+}$, or decaying outside the detector.

[106] ABBIENDI 02C searches for pair production of $H^{++}H^{--}$, with $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ (ℓ,ℓ' = e,μ,τ). The limit holds for ℓ=ℓ'=τ, and becomes stronger for other combinations of leptonic final states. To ensure the decay within the detector, the limit only applies for $g(H\ell\ell) \gtrsim 10^{-7}$.

[107] AKTAS 06A search for single $H^{\pm\pm}$ production in ep collisions at HERA. Assuming that H^{++} only couples to $e^{+}\mu^{+}$ with $g_{e\mu}$ = 0.3 (electromagnetic strength), a limit $m_{H^{++}} > 141$ GeV (95% CL) is derived. For the case where H^{++} couples to $e\tau$ only the limit is 112 GeV.

[108] ACOSTA 05L search for $H^{++}H^{--}$ pair production in $p\overline{p}$ collisions. The limit is valid for $g_{\ell\ell'} < 10^{-8}$ so that the Higgs decays outside the detector.

[109] ABBIENDI 03Q searches for single $H^{\pm\pm}$ via direct production in $e^{+}e^{-} \rightarrow e^{\pm}e^{\pm}H^{\mp\mp}$, and via t-channel exchange in $e^{+}e^{-} \rightarrow e^{+}e^{-}$. In the direct case, and assuming B($H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$) = 1, a 95% CL limit on $h_{ee} < 0.071$ is set for $m_{H^{\pm\pm}} < 160$ GeV (see Fig. 6). In the second case, indirect limits on h_{ee} are set for $m_{H^{\pm\pm}} < 2$ TeV (see Fig. 8).

[110] GORDEEV 97 search for muonium-antimuonium conversion and find $G_{M\overline{M}}/G_F < 0.14$ (90% CL), where $G_{M\overline{M}}$ is the lepton-flavor violating effective four-fermion coupling. This limit may be converted to $m_{H^{++}} > 210$ GeV if the Yukawa couplings of H^{++} to ee and $\mu\mu$ are as large as the weak gauge coupling. For similar limits on muonium-antimuonium conversion, see the muon Particle Listings.

[111] ASAKA 95 point out that H^{++} decays dominantly to four fermions in a large region of parameter space where the limit of ACTON 92M from the search of dilepton modes does not apply.

[112] ACTON 92M limit assumes $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ or $H^{\pm\pm}$ does not decay in the detector. Thus the region $g_{\ell\ell} \approx 10^{-7}$ is not excluded.

[113] ACTON 92M from $\Delta\Gamma_Z$ <40 MeV.

[114] SWARTZ 90 assume $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ (any flavor). The limits are valid for the Higgs-lepton coupling g($H\ell\ell$) $\gtrsim 7.4 \times 10^{-7}/[m_H/\mathrm{GeV}]^{1/2}$. The limits improve somewhat for ee and $\mu\mu$ decay modes.

LIMITS for $H^{\pm\pm}$ with $T_3 = 0$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$>$ 98.2	95	[115] ABAZOV	04E	D0	$\mu\mu$
>113	95	[116] ACOSTA	04G	CDF	$\mu\mu$
$>$ 97.3	95	[117] ABDALLAH	03	DLPH	$\tau\tau$
$>$ 97.3	95	[118] ACHARD	03F	L3	$\tau\tau$
$>$ 98.5	95	[119] ABBIENDI	02C	OPAL	$\tau\tau$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[120] AKTAS	06A	H1	single $H^{\pm\pm}$
>109	95	[121] ACOSTA	05L	CDF	stable
		[122] ABBIENDI	03Q	OPAL	$E_{cm} \leq$ 209 GeV, single $H^{\pm\pm}$
		[123] GORDEEV	97	SPEC	muonium conversion
$>$ 45.6	95	[124] ACTON	92M	OPAL	
$>$ 25.5	95	[125] ACTON	92M	OPAL	
none 7.3–34.3	95	[126] SWARTZ	90	MRK2	

[115] ABAZOV 04E search for $H^{++}H^{--}$ pair production in $H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$. The limit is valid for $g_{\mu\mu} \gtrsim 10^{-7}$.

[116] ACOSTA 04G search for $H^{++}H^{--}$ pair production in $p\overline{p}$ collisions with muon and electron final states. The limit holds for $\mu\mu$.

[117] ABDALLAH 03 search for $H^{++}H^{--}$ pair production either followed by $H^{++} \rightarrow \tau^{+}\tau^{+}$, or decaying outside the detector.

[118] ACHARD 03F search for $e^{+}e^{-} \rightarrow H^{++}H^{--}$ with $H^{\pm\pm} \rightarrow \ell^{\pm}\ell'^{\pm}$. The limit holds for $\ell = \ell' = \tau$, and slightly different limits apply for other flavor combinations. The limit is valid for $g_{\ell\ell'} \gtrsim 10^{-7}$.

[119] ABBIENDI 02C searches for pair production of $H^{++}H^{--}$, with $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ (ℓ,ℓ' = e,μ,τ). the limit holds for ℓ=ℓ'=τ, and becomes stronger for other combinations of leptonic final states. To ensure the decay within the detector, the limit only applies for $g(H\ell\ell) \gtrsim 10^{-7}$.

[120] AKTAS 06A search for single $H^{\pm\pm}$ production in ep collisions at HERA. Assuming that H^{++} only couples to $e^{+}\mu^{+}$ with $g_{e\mu}$ = 0.3 (electromagnetic strength), a limit $m_{H^{++}} >$ 141 GeV (95% CL) is derived. For the case where H^{++} couples to $e\tau$ only the limit is 112 GeV.

[121] ACOSTA 05L search for $H^{++}H^{--}$ pair production in $p\overline{p}$ collisions. The limit is valid for $g_{\ell\ell'} < 10^{-8}$ so that the Higgs decays outside the detector.

[122] ABBIENDI 03Q searches for single $H^{\pm\pm}$ via direct production in $e^{+}e^{-} \rightarrow e^{\pm}e^{\pm}H^{\mp\mp}$, and via t-channel exchange in $e^{+}e^{-} \rightarrow e^{+}e^{-}$. In the direct case, and assuming B($H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$) = 1, a 95% CL limit on $h_{ee} <$ 0.071 is set for $m_{H^{\pm\pm}} <$ 160 GeV (see Fig. 6). In the second case, indirect limits on h_{ee} are set for $m_{H^{\pm\pm}} <$ 2 TeV (see Fig. 8).

[123] GORDEEV 97 search for muonium-antimuonium conversion and find $G_{M\overline{M}}/G_F <$ 0.14 (90% CL), where $G_{M\overline{M}}$ is the lepton-flavor violating effective four-fermion coupling. This limit may be converted to $m_{H^{++}} >$ 210 GeV if the Yukawa couplings of H^{++} to ee and $\mu\mu$ are as large as the weak gauge coupling. For similar limits on muonium-antimuonium conversion, see the muon Particle Listings.

[124] ACTON 92M limit assumes $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ or $H^{\pm\pm}$ does not decay in the detector. Thus the region $g_{\ell\ell} \approx 10^{-7}$ is not excluded.

[125] ACTON 92M from $\Delta\Gamma_Z$ <40 MeV.

[126] SWARTZ 90 assume $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ (any flavor). The limits are valid for the Higgs-lepton coupling g($H\ell\ell$) $\gtrsim$ 7.4 $\times 10^{-7}/[m_H/\mathrm{GeV}]^{1/2}$. The limits improve somewhat for ee and $\mu\mu$ decay modes.

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ABAZOV	06J	PRL 97 121802	V.M. Abazov *et al.*	(D0 Collab.)
ABAZOV	06O	PRL 97 151804	V.M. Abazov *et al.*	(D0 Collab.)
ABAZOV	06Q	PRL 97 161803	V.M. Abazov *et al.*	(D0 Collab.)
ABULENCIA	06	PRL 96 011802	A. Abulencia *et al.*	(CDF Collab.)
ABULENCIA	06E	PRL 96 042003	A. Abulencia *et al.*	(CDF Collab.)
ABULENCIA	06H	PRL 96 081803	A. Abulencia *et al.*	(CDF Collab.)
ABULENCIA,A	06A	PRL 97 081802	A. Abulencia *et al.*	(CDF Collab.)
AKTAS	06A	PL B638 432	A. Aktas *et al.*	(H1 Collab.)
LEP-SLC	06	PRPL 427 257	ALEPH, DELPHI, L3, OPAL, SLD and working groups	
SCHAEL	06B	EPJ C47 547	S. Schael *et al.*	(LEP Collabs.)
ABAZOV	05F	PRL 94 091802	V.M. Abazov *et al.*	(D0 Collab.)
ABAZOV	05T	PRL 95 151801	V.M. Abazov *et al.*	(D0 Collab.)
ABBIENDI	05A	EPJ C40 317	G. Abbiendi *et al.*	(OPAL Collab.)
ABDALLAH	05D	EPJ C44 147	J. Abdallah *et al.*	(DELPHI Collab.)
ACHARD	05	PL B609 35	P. Achard *et al.*	(L3 Collab.)
ACOSTA	05K	PRL 95 051801	D. Acosta *et al.*	(CDF Collab.)
ACOSTA	05L	PRL 95 071801	D. Acosta *et al.*	(CDF Collab.)
ACOSTA	05Q	PR D72 072004	D. Acosta *et al.*	(CDF Collab.)
ABAZOV	04E	PRL 93 141801	V.M. Abazov *et al.*	(D0 Collab.)
ABBIENDI	04	EPJ C32 453	G. Abbiendi *et al.*	(OPAL Collab.)
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ABBIENDI	04M	EPJ C37 49	G. Abbiendi *et al.*	(OPAL Collab.)
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ACOSTA	04G	PRL 93 221802	D. Acosta *et al.*	(CDF Collab.)
ABBIENDI	03	PL B551 35	G. Abbiendi *et al.*	(OPAL Collab.)
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ABDALLAH	03	PL B552 127	J. Abdallah *et al.*	(DELPHI Collab.)
ACHARD	03C	PL B568 191	P. Achard *et al.*	(L3 Collab.)
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HEISTER	03D	PL B565 61	A. Heister *et al.*	(ALEPH, DELPHI, L3+)
ALEPH, DELPHI, L3, OPAL, LEP Higgs Working Group				
ABAZOV	02B	PRL 88 151803	V.M. Abazov *et al.*	(D0 Collab.)
ABBIENDI	02C	PL B526 221	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	02D	EPJ C23 397	G. Abbiendi *et al.*	(OPAL Collab.)
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AKEROYD	02	PR D66 037702	A.G. Akeroyd *et al.*	
BORZUMATI	02	PL B549 170	F.M. Borzumati, A. Djouadi	
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HEISTER	02	PL B526 191	A. Heister *et al.*	(ALEPH Collab.)
HEISTER	02L	PL B544 16	A. Heister *et al.*	(ALEPH Collab.)
HEISTER	02M	PL B544 25	A. Heister *et al.*	(ALEPH Collab.)
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ABAZOV	01E	PRL 87 231801	V.M. Abazov *et al.*	(D0 Collab.)
ABBIENDI	01A	EPJ C19 587	G. Abbiendi *et al.*	(OPAL Collab.)
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ACCIARRI	00M	PL B485 85	M. Acciarri *et al.*	(L3 Collab.)
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ABBIENDI	99O	PL B464 311	G. Abbiendi *et al.*	(OPAL Collab.)
ABBOTT	99B	PRL 82 2244	B. Abbott *et al.*	(D0 Collab.)
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MANGANO	97	PL B410 299	M. Mangano, S. Slabospitsky	
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ALCARAZ	96	CERN-PPE/96-183	J. Alcaraz *et al.*	
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ALEXANDER	96H	ZPHY C71 1	G. Alexander *et al.*	(OPAL Collab.)
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GURTU	96	PL B385 415	A. Gurtu	(TATA)
PDG	96	PR D54 1	R. M. Barnett *et al.*	
ABREU	95H	ZPHY C67 69	P. Abreu *et al.*	(DELPHI Collab.)
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